

METHOD AND APPARATUS REDUCING OFF TRACK HEAD MOTION DUE TO DISK
VIBRATION IN A HARD DISK DRIVE USING CONFIGURATION OF THE DISK DRIVE
SERVO CONTROLLER

BACKGROUND OF THE INVENTION

1. Field of the Invention

5 The present invention relates to head gimbal assemblies and servo controller of a hard disk drive.

2. Background Information

10 Hard disk drives contain a plurality of magnetic heads that are coupled to rotating disks. The heads write and read information by magnetizing and sensing the magnetic fields of the disk surfaces. There have been developed magnetic heads that have a write element for magnetizing the disks and a separate read element for sensing the magnetic field of the disks. The read element is typically constructed from a magneto-resistive material. The magneto-resistive
15 material has a resistance that varies with the magnetic fields of the disk. Heads with magneto-resistive read elements are commonly referred to as magneto-resistive (MR) heads.

 Each head is embedded in a slider, which is attached to a flexure arm to create a subassembly commonly referred to as a head gimbal assembly (HGA). The HGA's are attached to an actuator arm. The actuator arm has a voice coil motor that can move the heads across the
20 surfaces of the disks.

 Information is stored in radial tracks that extend across the surfaces of each disk. Each track is typically divided up into a number of segments or sectors. The voice coil motor and actuator arm can move the heads to different tracks of the disks and to different sectors of each track.

A suspension interconnect extends along the length of the flexure arm and connects the head to a preamplifier. The suspension interconnect typically comprises a pair of conductive write traces and a pair of conductive read traces. One pair of traces, such as the read traces, extend down one side of the flexure arm to the head and the remaining pair of traces extends
5 down the other side of the flexure arm to the head.

The Tracks Per Inch (TPI) in hard disk drives is rapidly increasing, leading to smaller and smaller track positional tolerances. The track position tolerance, or the offset of the read-write head from a track, is monitored by a signal known as the head Positional Error Signal (PES). Reading a track successfully usually requires minimizing read-write head PES occurrences. The
10 allowable level of PES is becoming smaller and smaller. A substantial portion of the PES is caused by disk vibration.

Track Mis-Registration (TMR) occurs when a read-write head tends to lose the track registration. This occurs when the disk surface bends up or down. TMR is often a statistical measure of the positional error between a read-write head and the center of an accessed track.
15 Bending is defined in terms of bending modes. For a positive integer k , a bending mode of $(k,0)$ produces k nodal lines running through the disk surface center, creating k peaks and k troughs arranged on the disk surface. Bending mode $(0,0)$ produces no nodal lines, either the entire disk is bent up or bent down.

Two basic prior art approaches are known to lower the Track Mis-Registration (TMR) due to disk vibration. One approach uses head gimbal assemblies providing a radial motion
20 capability. The other approach alters the servo-controller to reduce TMR.

In the first approach, a head gimbal assembly, including a biased load beam, creates a roll center (also known as a dimple center), which provides a radial motion capability as the load beam moves vertically due to disk vibration. This allows sliders to move in a radial direction as
25 well as in a vertical direction with respect to the disks, reducing off-track motion due to disk vibration.

The first approach has some problems. An air bearing forms between the slider face and the disk surface. The slider face is tilted near the disk surface when it is flat. The air bearing

becomes non-uniform when the disk surface is flat, adding new mechanical instabilities into the system.

One alternative prior art head gimbal assembly provides a slider mounted so that it pivots in the radially oriented plane about the effective roll axis, which is located within the disk. This scheme does not cause a non-uniform air bearing when the disk surface is flat. However, the way the effective roll axis is placed inside the disk requires a more complex mechanical coupling between the slider support assembly and the slider. This complex mechanical coupling may have a greater probability of mechanical failure, tending to increase manufacturing expenses and to reduce hard disk drive life expectancy.

The second prior art approach to lowering TMR due to disk vibration alters the servo-controller. These servo controllers favor optimization of PES in the disk vibration range without regard for strengthening rejection of low frequency disturbances. The disk vibration range will be considered to include frequencies between about 1K Hz and about 4K Hz. Low frequency disturbances will be considered to include at least the frequencies between about 0 Hz and about 800 Hz.

Accordingly, there exists a need for head gimbal assembly mechanisms providing a stable air bearing, able to follow a track when a disk surface bends, which are easy and reliable to manufacture. There exists a need for servo controllers optimizing PES in the disk vibration range and taking into account potential advantages from strengthened rejection of low frequency disturbances.

BRIEF SUMMARY OF THE INVENTION

The present invention provides a distinctive servo-controller scheme resulting in overall improvement in PES performance, particularly when applied to hard disk drives employing the invention's Track Mis-Registration (TMR) reduction mechanisms.

The servo-controllers trade off gain in the disk vibration frequency range in favor of increased rejection of low frequency disturbances. This leads to the lowest PES statistics, when applied to hard disk drives with the TMR reduction mechanisms of the invention.

The present invention includes improved head gimbal assemblies, which address TMR. These head gimbal assemblies may be as mechanically simple as contemporary head gimbal assemblies, support parallel flying sliders over flat disk surfaces, and reduce TMR induced by disk vibration. They may be easier to build, more reliable, and cost less to make, than other
5 known approaches, at comparable track densities and rotational rates. They include mechanisms moving the slider parallel the disk surface, when the disk surface is flat, and radially moving the slider toward the track, when the disk surface is bent, so that the head can more closely follow the track.

In a first set of mechanisms, the actuator arm moves by lever action through a principal
10 axis, with the slider aligned at a bias angle and the slider face parallel to the flat disk surface. The lever action causes the slider to move radially toward the track, when the disk surface is bent.

In a second set of mechanisms, the actuator arms couple to load beams via two fingers. The first finger flexes differently from the second finger when the disk surface is bent. The
15 fingers are constructed so that when the disk surface is bent, the slider is moved radially toward the track.

A third set of mechanisms move the actuator arm by lever action through the principal axis. The actuator holds the slider parallel to the disk surface, when it is flat. The slider is mounted by a flexure at a second bias angle to the principal axis. The flexure responds as the
20 disk surface bends through the second bias angle, causing the slider to move radially toward the track.

The present invention also provides head gimbal assemblies incorporating mechanisms of the first set operating with mechanisms of the third set. The invention alternatively provides head gimbal assemblies incorporating mechanisms of the second set operating with mechanisms of the
25 third set.

BRIEF DESCRIPTION OF THE DRAWINGS

The objects and features of the present invention, which are believed to be novel, are set forth with particularity in the appended claims. The present invention, both as to its organization and manner of operation, together with further objects and advantages, may best be understood
5 by reference to the following description, taken in connection with the accompanying drawings, in which:

Figure 1 is a simplified schematic of the relationship between a principal axis of the actuator arm, head gimbal assembly, slider, and radial vector from the center of the spindle hub;

Figure 2 is a simplified schematic of a disk drive controller controlling a hard disk drive;

10 Figure 3A is a cross section view through a disk of a first inventive mechanism operating when the disk surface bends down;

Figure 3B is a radial-directional view through the disk of the first inventive mechanism, when the disk surface bends down;

Figure 3C is a cross section view through the disk of the first inventive mechanism
15 operating when the disk surface bends up;

Figure 3D is a radial-directional view through the disk of the first inventive mechanism operating when the disk surface bends up;

Figures 4A to 6A are top views of head gimbal assemblies of the first and second
inventive mechanisms;

20 Figures 6B to 6E are views of head gimbal assemblies of the second inventive mechanism;

Figure 7A is a top view of a head gimbal assembly of the first and second inventive mechanisms;

Figures 7B to 8D are views of a head gimbal assembly of the third inventive mechanism;

25 Figures 9A, 9C, and 9E are side views of the radial head motions for head gimbal assemblies of Figure 8D, resulting from the bending motion of the flexure gimbal induced by disk axial vibration;

Figures 9B, 9D, and 9F are top views of the radial head motions for head gimbal assemblies of Figure 8D, resulting from the bending motion of the flexure gimbal induced by disk axial vibration;

Figures 10A, 10C, and 10E are side views of the radial head motions for head gimbal assemblies of Figure 7B, resulting from the bending motion of the flexure gimbal induced by disk axial vibration;

Figures 10B, 10D, and 10F are top views of the radial head motions for head gimbal assemblies of Figure 7B, resulting from the bending motion of the flexure gimbal induced by disk axial vibration;

Figures 11A and 11B are cross section and radial-directional views, through the disk, of the mechanisms of Figures 7B through 8D operating when the disk surface bends down;

Figures 11C and 11D are cross section and radial-directional views, through the disk, of the mechanisms of Figures 7B through 8D operating when the disk surface bends up;

Figure 12 is a graph of the results of the bending slope per unit of axial displacement for four common bending modes for various radial positions and ID through OD;

Figures 13A, 13B, and 13C are graphs summarizing results regarding the power spectral density function in terms of axial vibration frequency versus displacement in meters at ID, at MD, and at OD, respectively;

Figure 14A is the geometric analysis used for the roll bias angle formula for the mechanisms of Figures 7B to 8D when the disk surface bends down as in Figure 11A;

Figure 14B is the geometric analysis used for the roll bias angle formula for the mechanisms of Figures 7B to 8D, when the disk surface bends up as in Figure 11C;

Figure 14C is the geometric analysis used for the roll bias angle formula for the roll center mechanisms of Figures 4A to 7A when the disk surface bends down as in Figure 8A;

Figure 14D is the geometric analysis used for the roll bias angle formula for the roll center mechanisms of Figures 4A to 7A when the disk surface bends up as in Figure 9A;

Figures 15A and 15B are graphs of the results of the bending angle versus the roll bias angle at OD when the disk is respectively bent down and bent up;

Figure 16A is a graph summarizing the spectral density of NRRO PES/Track pitch measure in percent versus vibrational frequency for a disk-head gimbal assembly with a roll bias angle of zero degrees, which is standard in conventional hard disk drives;

Figures 16B and 16C are graphs summarizing the spectral densities of NRRO PES/Track pitch measure in percent versus vibrational frequency for a disk-head gimbal assembly with a roll bias angle of one degree and of two degrees, respectively;

Figure 17 is a graph of a weight function for PES feedback in the frequency domain trading servo controller gain in disk vibration frequency range for increased rejection of low frequency disturbances;

Figure 18 is a graph of the error sensitivity function of the original servo controller and the modified servo controller as derived from Figure 17;

Figure 19 is a graph of the mechanical disturbance spectra of the in-plane torque disturbance spectrum and out-of-plane disk disturbance spectrum; and

Figures 20 and 21 are graphs of the results regarding a conventional disk-head gimbal assembly interface, compared to a head-gimbal assembly, with a two degree roll bias angle, operated with the modified servo-controller.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The following description is provided to enable any person skilled in the art to make and use the invention and sets forth the best modes presently contemplated by the inventors of carrying out the invention. Various modifications, however, will remain readily apparent to those skilled in the art, since the generic principles of the present invention have been defined herein.

Disclosed are improved head gimbal assemblies addressing Track Mis-Registration (TMR). These head gimbal assemblies may be as mechanically simple as contemporary head gimbal assemblies, support parallel flying sliders over flat disk surfaces, and reduce TMR induced by disk vibration. They are easier to build, more reliable, and cost less to make, than other known approaches at comparable track densities and rotational rates. The improved head gimbal assemblies include improved suspensions or mechanisms for moving the slider parallel to

the disk surface, when the disk surface is flat, and radially moving the slider toward the track, when the disk surface is bent.

Referring to the drawings, more particularly by reference numbers, Figure 1 shows an example actuator arm assembly pivoting about the actuator axis 40, changing the angle between the radial vector 112 and the actuator principal axis 110. The actuator arm assembly includes the actuator arm 50 coupled to head gimbal assembly 60, which is coupled to slider 100. Typically, the actuator arm assembly will rotate through various angles between a furthest inside position of the disk and the furthest outside position on the disk. Test data and analyses are provided for three regions of the disk. These are designated ID (corresponding to the furthest inside position), MD (a middle position where radial vector 112 is approximately at a right angle with 110), and OD (the furthest outside position).

In Figure 1, an X axis extends along the principal axis 110 of the actuator arm, and a Y axis intersects the X axis at essentially actuator pivot 40. When the actuator arm 50 positions the slider 100 so that the read-write head is at MD, the radial vector 112 is nearly parallel to the Y axis. Track 18 is shown near MD, but tracks exist from ID to OD, across the disk surface 12.

The hard disk drive may include a plurality of actuator arms and head sliders located adjacent to the disks all controlled by the same voice coil motor. The heads may have separate write and read elements, that magnetize and sense the magnetic field of the disks.

Figure 2 shows a schematic of an example controller system for a disk drive. The controller system includes a voice coil 32 coupled to a magnet assembly to create a voice coil motor. Providing a current to the voice coil 32 creates a torque that swings the actuator arm 50, contained in the actuator assembly 30. Moving the actuator arm 50 moves the actuator arm assembly, which moves the heads across the surfaces of the disk 12.

The hard disk drive may further include a disk drive controller 1000. In Figure 2, disk drive controller 1000 communicates with an analog read-write interface 220, which in turn communicates the resistivity found in the spin valve within read-write head to controller 1000. The analog read-write interface 220 frequently includes a channel interface 222 communicating with a pre-amplifier 224. The channel interface 222 receives commands from the embedded disk controller 1000, setting the read_bias and write_bias. The analog read-write interfaces 220

may employ either a read current bias or a read voltage bias. For example, the resistance of the read head is determined by measuring the voltage drop (V_{rd}) across the read differential signal pair ($r+$ and $r-$), based upon the read bias current setting $read_bias$, using Ohm's Law.

In Figure 2, the channel interface 222 provides a Position Error Signal (PES) to the servo controller 240, which controls voice coil 32 to keep the read-write head close enough to access a data track (such as track 18 of Figure 1).

The invention includes three approaches for addressing the TMR problem by moving the slider face parallel to the disk surface with respect to the track when the disk surface is flat, and a moving the slider toward the track when the disk surface is bent. Each of these approaches for reducing TMR may be used individually or in combination with other approaches discussed herein or elsewhere.

Actuator assemblies using example mechanisms employing the first approach are seen in Figures 4A to 6A and 7A. In these example mechanisms the actuator arm moves by lever action through a principal axis, with the slider aligned at a bias angle and the slider face parallel to the flat disk surface. The lever action causes the slider to move radially toward the track, when the disk surface is bent.

In addition to the example mechanisms employing the first approach, Figures 4A to 6A also show actuators with example mechanisms employing the second approach. Figures 6B to 6E show actuator assemblies which use only the second approach to reducing TMR. As will be explained further below, the example mechanisms employing the second approach include two fingers coupling the actuator arm to the load beam, where the fingers flex differently from each other when the disk surface is bent. The difference in the response of each finger to the bending of the disk surface is designed to cause the slider to move radially toward the track when the disk surface bends.

Figures 7B to 8D show example mechanisms employing the third approach to reducing TMR. In these mechanisms, the slider is mounted by a flexure at a second bias angle to the principal axis. The actuator holds the slider parallel to the disk surface, when it is flat. The flexure responds as the disk surface bends through the second bias angle, causing the slider to move radially toward the track.

In operation, these mechanisms provide a suspension with a roll center movable slider which allows the read-head to follow a track as the disk surface bends. This process is seen more clearly in reference to Figures 3A to 3D which show schematically the head-disk interface dynamics. Figures 3A and 3B show cross section and radial-directional views through the disk 14 of the inventive mechanisms discussed above operating when the disk surface 12 bends down, and Figures 3C and 3D show cross section and radial-directional views through the disk 14 of a first inventive mechanism operating when the disk surface 12 bends up.

Throughout this document, the read-write head position when the disk surface is flat is denoted A0, and when bent is denoted A1. The track position when the disk surface is flat is denoted B0, and when bent, is denoted B1. δ refers to the amount of this off-track movement, or the distance between A1 and B1. δ_1 refers to the distance between A0 and A1. δ_2 refers to the distance between B0 and B1.

This head-disk surface interface allows the use of the formula $\delta = \delta_1 + \delta_2$, for the motion of Figures 3A and 3C, given that A0-B0 and A1-B1 are essentially 0, because

$$\begin{aligned} \text{Distance}(A1-B1) &= \text{Distance}(A1-A0+A0-B1+B0-B0) \\ &= \text{Distance}((A1-A0) + (B0-B1) + (A0-B0)) \\ &\approx \text{Distance}((A1-A0) + (B0-B1)) \end{aligned}$$

$$\delta \approx \delta_1 + \delta_2 = 0.$$

$$\text{In Figures 3A and 3C, } \delta_2 = td/2 * \theta = -\delta_1.$$

Each of the previously mentioned approaches will be discussed in more detail below.

Figures 4A to 6A, and 7A, show several means for moving the slider parallel to a disk surface. Including moving the actuator arm by a lever action through the principal axis with the slider aligned at a bias angle 710, when the slider face is essentially parallel to the disk surface.

With respect to the track when the disk surface is flat, Figures 4A to 6A, and 7A, show the means for radially moving the slider. Each of which includes a means for the lever action to cause the slider to move radially bent. More specifically, the lever action through the principal axis at the bias angle 710, causes the radial motion of the slider. In these Figures, the dynamics

of the head-disk interface determine the bias angle 710, which is preferably between plus and minus 10 degrees from zero.

In Figure 4A, a head gimbal assembly includes a suspension having bias angle 710, attached by connection beam 82 to extended base plate 84. The suspension mounts on the actuator arm, at bent edge 700 of extended base plate 84 and at bent edge 702 of load beam 80.

In Figure 4B, a head gimbal assembly includes a suspension having bias angle 710, attached to base plate 70. It mounts on the actuator arm, at bent edge 704 of base plate 70 and at bent edge 700 of load beam 80.

In Figure 4C, a head gimbal assembly includes a suspension having bias angle 710, attached by connection beam 82 to extended base plate 84. This is mounted on the actuator arm, at the bent edge 700 of the extended base plate 84.

In Figure 4D, a head gimbal assembly includes a suspension having bias angle 710, attached to base plate 70, which is mounted on the actuator arm, at bent edge 704 of base plate 70.

Figures 4A to 6B, and 7A, show the second inventive mechanism for reducing TMR. This includes the means for moving the actuator arm coupled to the load beam via two fingers. The first finger flexes differently from the second finger when the disk surface is bent. The first finger flexes differently from the second finger, causing the slider to move radially with respect to the track when the disk surface is bent.

In particular, Figures 6B to 6E show embodiment of the second mechanism, which do not involve a bias angle 710 as shown in Figures 4A to 6A and 7A. Figure 6B shows a top view of a head gimbal assembly, based upon the difference in the connection beam fingers 82-A and 82-B connecting up 83-A and down 83-B, respectively. Finger 82-A flexes differently from finger 82-B, causing slider 100 to move radially with respect to the track, as disk surface 12 is bent. Figure 6C shows fingers 82-A and 82-B connecting up and down on the upper connection beam 86 and lower connection beam, as in Figure 6E. Figures 6D and 6E show side views of the head gimbal assembly of Figure 6B when the thickness of the base plate 70 and load beam 80 differ, or are the same, respectively. Extended base plate 84, finger 82-A, and upper connection beam 86 are preferably made from one sheet of metal, preferably stainless steel.

Figure 7A shows a top view of suspension 80 attached to base plate 70 using a cutout 720 to create fingers 80-A and 80-B, which together form bias angle 710. The bias angle 710 can be determined by the dynamics of the head-disk interface, the shape of cut-out 720, and the stiffness of load beam 80.

5 Figures 7B to 8D show examples of a third inventive mechanisms for reducing TMR. This includes moving the actuator arm by the lever action through the principal axis when the slider is parallel to the disk surface. The slider is mounted on a flexure at a second bias angle 710 to the principal axis. The means for radially moving the slider includes the flexure responding as the disk surface bends through the second bias angle, causing the slider to move
10 radially toward the track.

Figure 7B shows a top view of the suspension attached to base plate 70, with two points 722 and 724 welding flexure 90 to load beam 80, providing bias angle 710. Flexure 90 attaches to both slider 100 and to load beam 80. The number of welding points close to the slider is preferably at least two. If the line between welding points is not perpendicular to the principal
15 axis 110, then the trajectory of bending motion of the flexure induced by disk axial vibration will be on a tilted bending line. It is sometimes preferred that the line, between the welding points 722 and 724, is not perpendicular to the principal axis 110.

Figures 9A to 9F show radial head motions for the head gimbal assembly of Figure 8D, due to the bending motion of the flexure gimbal induced by disk axial vibration. In Figures 9B, 9D, and 9F, the trajectory of head, moves about the tilted bending line 740. This line is
20 preferably in a range of plus or minus 10 degrees of arc from zero.

Figures 10A to 10F show radial head motions for the head gimbal assembly of Figure 7B, according to the bending motion of the flexure gimbal induced by the disk axial vibration. In Figures 10B, 10D, and 10F, the trajectory of head, moves about the tilted bending line 740. This
25 line is again, preferably, in a range of plus or minus 10 degrees of arc from zero.

Embodiments of a third set of example mechanisms built according to the invention are shown in Figures 7B through 8D. Figures 11A to 11D show various views of this set of mechanisms.

Figure 11A shows a cross section view, through disk 14 when the disk surface 12 bends down 12-A. Figure 11B shows a radial-directional view when disk surface 12 bends up 12-B.

Figure 11C shows a cross section view when the disk surface 12 bends up 12-B. Figure 11D shows a radial-directional view when the disk surface 12 bends up 12-B.

It is reasonable to use the formula $\delta = \delta_1 - \delta_2 = 0$, for the motion of Figures 11A and 11C, since A_0-B_0 and A_1-B_1 are essentially 0, leading, as in Figure 3C, to $\delta_2 = td/2 * \theta = -\delta_1$.

Figure 12 shows the results of the bending slope per unit axial displacement, for various radial positions for four common bending modes for ID through OD. The horizontal axis indicates radial position in terms of meters. The vertical axis indicates the bending slope per unit axial displacement in terms of 1/meter. Trace 800 indicates the results for bending mode (3,0). Trace 802 indicates the results in bending mode (2,0). Trace 804 indicates the results in bending mode (1,0). Trace 806 indicates the results in bending mode (0,0).

Figures 13A, 13B, and 13C summarize results regarding the power spectral density function in terms of axial vibration frequency versus displacement in meters at ID, at MD, and at OD, respectively.

In Figures 12 through 13C, the experimental hard disk drive was rotating at 7200 RPM.

Figures 14A and 14B show the geometric analysis used for the bias angle 710 formula for the mechanisms of Figures 7B to 8D when the disk surface bends down as in Figure 11A and bent up as in Figure 11C. In these Figures:

A refers to the upper center point of slider 100 for the stationary state.

C refers to upper center point of slider 100 for the disk spinning state.

c refers to a deformed track 18 on the spinning disk surface 12.

ts refers to the thickness of slider 100.

td refers to the thickness of disk 14.

θ refers to the disk bending angle.

r refers to the radius of the disk, which is preferably 45 mm.

ϕ refers to the roll bias angle, which is portrayed in Figures 7B to 8D by reference number 710.

In Figures 14A to 14D, the bending angle per unit of axial vibration at r was experimentally determined to be

75/m for bending mode (3,0),

60/m for bending mode (2,0),

5 50/m for bending mode (1,0), and

40/m for bending mode (0,0).

The bias angle 710 of the earlier Figures is the roll bias angle ϕ of Figures 14A-16C. In Figure 14A, the roll bias angle $\phi = \arccos((a - b \cos \theta) / c)$ for the disk bending down. In Figure 14B, the roll bias angle $\phi = \arccos((b \cos \theta - d) / c)$ for the disk bending up. This leads to $\phi \approx$
 10 1.2 degrees of arc at the Outside position of Disk OD, with $r = 45$ mm. In Figures 14A and 14B, the radial motion of slider 100 is about $h = b * \sin \theta = (ts + td/2) \sin \theta$.

Figure 14C shows the geometric analysis of the roll bias angle 710 formula for the roll center mechanisms of Figures 4A to 6A, and 7A, when the disk surface bends down as in Figure 8A.

15 Figure 14D shows the geometric analysis of the roll bias angle 710 formula for the roll center mechanisms of Figures 4A to 6A, and 7A, when the disk surface bends up as in Figure 9A.

In Figures 14C and 14D:

Ar refers to the roll center for the stationary state.

20 Cr refers to roll center for the disk spinning state.

c refers to a deformed track 18 on the spinning disk surface 12.

ts refers to the thickness of slider 100.

td refers to the thickness of disk 14.

θ refers to the disk bending angle.

25 r refers to the radius of the disk, which is preferably 45 mm.

ϕ refers to the roll bias angle, which is portrayed in Figures 4A to 6A, and 7A by reference number 710.

In Figure 14C, the roll bias angle $\phi = \arccos((ar - br \cos \theta) / cr)$ for the disk bending down. In Figure 14D, the roll bias angle $\phi = \arccos((br \cos \theta - dr) / cr)$ for the disk bending up. This leads to $\phi \approx 1.6$ degrees of arc at the Outside position of Disk OD, with $r = 45$ mm.

Drive level experiments were conducted on two types of production hard disk drives with the roll biased load beam built to move the roll center radially as shown in Figure 5A. The hard disk drives operated at 56,000TPI at 7200 RPM and at 93,000 TPI at 7200 RPM. Both types of hard disk drives were able to move the roll center radially with the biased load beam.

Skew angles as used herein refer to the angular difference from the perpendicular of the principal axis 110 of the actuator with respect to the tangent of the track 18. In the experimental hard disk drives, the skew angle at OD is about 13.1 degrees arc, at MD about -5 degrees arc, and at ID about -18 degrees arc. Please refer to Figure 1 for an illustration of these positions.

Figures 15A and 15B show the results regarding the bending angle versus the roll bias angle at OD when the disk bends down and up, respectively. The vertical axes represent the roll bias angle ϕ (710) in terms of degrees arc. The horizontal axes represent the bending angle in units of 10^{-5} degrees of arc.

The roll biased load beam acts to attenuate several peaks related to disk modes in the spectrum of the non-repeatable run-out (NRRO) PES signal, shown in Figures 16A-16C. In addition, the repeatable run-out (RRO) level is also attenuated, because of the attenuation of the NRRO in the writing of the servo track. The results in the following table are for tracks near OD.

Roll bias angle	Std-RRO (%)	Std-NRRO (%)	Std-Total (%)
Standard (0)	1.582	1.855	2.441
One degree	1.484	1.465	2.070
Two degrees	1.328	1.406	1.936

Figure 16A summarizes the spectral density 820 of NRRO PES/Track pitch measure in percent versus vibrational frequency for a disk-head gimbal assembly with no roll bias angle, which is standard in conventional hard disk drives. Figures 16B and 16C summarize the spectral

densities 822 and 824 of NRRO PES/Track pitch measure in percent versus vibrational frequency for a disk-head gimbal assembly with a roll bias angle of one degree and of two degrees, respectively.

In Figures 16A to 16C, the vertical axis represents NRRO per track pitch as a percentage.

5 The horizontal axis represents vibrational frequency in Herz.

Reference labels 1B and 1F represent the backward frequency and the forward frequency associated with bending mode (1,0).

Reference labels 2B and 2F represent the backward frequency and the forward frequency associated with bending mode (2,0).

10 Reference labels 3B and 3F represent the backward frequency and the forward frequency associated with bending mode (3,0).

Reference labels 4B and 4F represent the backward frequency and the forward frequency associated with bending mode (4,0).

15 TMR is further reduced by reconfiguring the servo controller 240 of Figure 2 for roll biased head gimbal assemblies, by sacrificing gain in the disk vibration region of the spectrum and increasing suppression in the low frequency region. In conventional hard disk drives, gain in the disk vibration frequency range cannot be sacrificed.

Figure 17 shows a weight function 840-848 for PES feedback in the frequency domain. The servo controller gain in disk vibration frequency range 842 to 846 is traded for increased rejection of low frequency disturbances 840. Figure 17 was derived by a random search method
20 with the weighted function for PES in the neighborhood ranges, 840-848.

Figure 18 shows the error sensitivity function of the original servo controller 850 and the modified servo controller 852 as derived from Figure 17. The vertical axis represents the error sensitivity in decibels. The horizontal axis represents the disk vibrational frequency in Herz.

25 F1 indicates a definition of disk vibration frequency range, from 1K Hz to 3K Hz. F2 indicates an alternative definition, from 800 Hz to 4K Hz.

F3 indicates a definition of low frequency range from 17 Hz to 800 Hz. F4 indicates an alternative definition, from 0 Hz to 800 Hz.

The preferred definition of disk vibration frequency range may vary among hard disk drives, possibly including higher and/or lower frequencies.

The preferred definition of low frequency range may vary among hard disk drives, possibly including higher and/or lower frequencies.

5 Figure 19 shows the mechanical disturbance spectra. Trace 860 represents the in-plane torque disturbance spectrum. Trace 862 represents the out-of-plane disk disturbance spectrum. References labels 3B, 3F, 4B, and 4F represent backward and forward resonance of bending modes (3,0) and (4,0). The vertical axis represents displacement on a logarithmic scale. The horizontal axis represents mechanical vibration in Herz.

10 Figures 20 and 21 show the results regarding a conventional disk-head gimbal assembly interface 870, compared to a head-gimbal assembly with a two degree roll bias angle, operated with the modified servo-controller 872. Trace 870 represents a conventional disk and head gimbal assembly interface with a total NRRO PES of 2.578%. Trace 872 represents the experimental hard disk drive with a roll bias angle of two degrees operated by the modified
15 servo-controller, having a total NRRO PES of 1.621%. This is a significant reduction in TMR, as measured by PES.

The invention includes applying this servo-controller scheme to any TMR reducing mechanism showing favorable results when trading off gain at the disk vibration frequency range in favor of increased rejection of low frequency disturbances.

20 Those skilled in the art will appreciate that various adaptations and modifications of the just-described preferred embodiments can be configured without departing from the scope and spirit of the invention. Therefore, it is to be understood that, within the scope of the appended claims, the invention may be practiced other than as specifically described herein.